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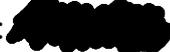
Experiment 6

Nuclear Magnetic Resonance


(Group 11)

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Tutor: 

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1 Abstract

With nuclear magnetic resonance the nuclear characteristics of atoms can be determined easily and non destructive. It is also used in medicine, for taking a look into humans. Therefore, in this experiment the nuclear magnetic moment μ_z of fluorine and the gyromagnetic ratio γ of hydrogen are measured by using a comparatively cheap setup. The setup used an electromagnetic high frequency oscillator and antenna to test a probe in a modulated magnetic field. This was analysed with an oscilloscope directly connected to the antenna and with the help of a lock-in amplifier. The final results are not significantly different to the literature values:

$$\mu_{z,F} = (13.287 \pm 0.010) \times 10^{-27} \text{ J/T}$$

for the magnetic moment of fluorine and

$$\gamma_{H_2} = (267.41 \pm 0.19) \times 10^6 \text{ rad/(s T)}$$

for the gyromagnetic ratio of hydrogen.

2 Introduction

Nuclear magnetic resonance (NMR) is an interesting effect with a lot of use cases, for example in medicine with the MRI or to determine the quantum magnetic properties of atomic nuclei in physical and chemical research.

NMR uses the difference in Zeemann-Levels from the nuclei induced by a strong magnetic field, to determine the element of the probe, or vice versa to determine the energy difference between the Zeemann-Levels at a given magnetic field strength from a specific element. This is used to determine the gyromagnetic ratio of hydrogen and fluorine.

The strength of magnetic fields can be measured by using a Hall sensor. In the sensor an electric field is generated in a way that the force on electrons from the magnetic field and from the electric field are compensated $F_B = -F_E$. The voltage needed is called Hall voltage U_H and is calculated with

$$U_H = \frac{IB}{ned}. \tag{1}$$

Here, n is the charge carrier density, d the conductor width and e the electron charge. The strength of the magnetic field is B and I is the current.

From now on I is the nuclear spin quantum number and the corresponding projection on the z-axis I_z can be observed.

$$\begin{aligned} |\vec{I}| &= \hbar\sqrt{I(I+1)} \\ \longrightarrow I_z &= m_i\hbar \quad (-I \leq m_i \leq I) \end{aligned} \tag{2}$$

So there are always $2I + 1$ different values for m_i and therefore also for I_z . For protons and neutrons $I_p = I_n = \frac{1}{2}$ so $m_i = \pm\frac{1}{2}$. Because of the Pauli principle always two nucleons pair together with opposite spins. Therefore, atoms with an even number of protons and neutrons have a total spin of $I = 0$. Atoms with an even number of protons and an odd number of neutrons or vice versa have a total spin of $I = \frac{1}{2}$, because one nucleon remains unpaired. Fluorine and hydrogen both have a spin of $I = \frac{1}{2}$. This quantum mechanic spin is connected to a magnetic dipole moment

$$\begin{aligned}\vec{\mu} &= \gamma \vec{I} \\ \longrightarrow \mu_z &= \gamma I_z\end{aligned}\tag{3}$$

also called nuclear magnetic moment. Similar to the Spin a projection on the z-axis can be made and the proportionality factor between both is the gyromagnetic ratio

$$\gamma = \frac{g_I \mu_N}{\hbar}.\tag{4}$$

In this formula, γ depends on g_I , the nuclear-g-factor, the nuclear magneton μ_N described by [equation \(5\)](#) and the Planck constant \hbar .

$$\mu_N = \frac{e\hbar}{2m_p}\tag{5}$$

The energy of a magnetic moment in an magnetic field is $E = -\vec{\mu} \cdot \vec{B}$. With the previous equations and $\vec{B} = B\vec{e}_z$, an energy difference $\Delta E = g_I \mu_N B$ between two states with $\Delta m_i = \pm 1$ can be calculated. This is known as the Zeemann split for nuclei. To change the orientation of the spin this energy is needed. When the atoms of a sample interact with photons for example emitted by an high frequency antenna the transmissions can be observed when the resonance frequency f is applied. In [equation \(6\)](#) this is seen together with the relation to the gyromagnetic ratio.

$$\begin{aligned}f &= \frac{\Delta E}{h} = \frac{g_I \mu_N B}{h} = \frac{\gamma B}{2\pi} \\ \longrightarrow \gamma &= 2\pi \frac{f}{B}\end{aligned}\tag{6}$$

This resonance can be detected in a certain frequency range and not at a sharp frequency because of an effect called spin-spin relaxation. The nuclei have a nuclear magnetic moment which induces a B -field at the place of a different nucleus. This results in a tiny shift of the resonance frequency up- or downwards. Finally, this widens up the range where the resonance frequency is found[5].

3 Methods

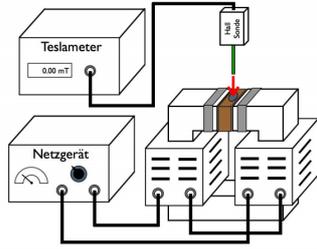


Figure 1: Setup for the measurement of the magnetic field[1]

The measurements have been conducted as described in the manual of the experiment[1]. The setup contains a pair of magnetic coils which are generating a magnetic field. This field is focused via two metal rods on to the probe where a homogeneous field arises.

Those two metal rods are equipped with two small modulation solenoids around it. In the middle of the metal rod is a high frequency (HF) oscillator and antenna with a hole inside, where samples can be inserted. For the first experiment, the setup shown in figure 1 is used but only the big coils are powered and a Hall sensor is connected to a teslameter. The sensor is then lowered into the hole to measure the strength of the magnetic field and to determine a depth

in which the field is homogeneous.

After that the setup is extended to measure the nuclear magnetic moment μ_z and the gyromagnetic ratio γ . The measurements are done with two different setups. For both of them the HF oscillator is connected to the corresponding controlling device with a display to read the set frequencies in MHz.

1. For the first setup shown in figure 2 the modulation magnetic coils are connected in a series connection to the control unit. This is in the same device as for the HF oscillator. Both signal outputs are connected to an oscilloscope to collect the data from the sine wave and the HF oscillator.

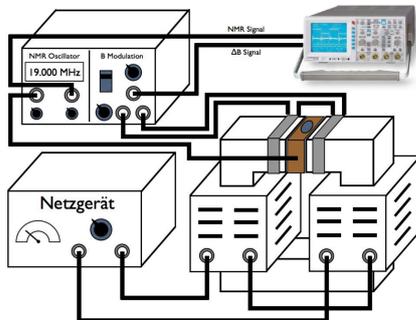


Figure 2: Setup with a modulated sine wave[1]

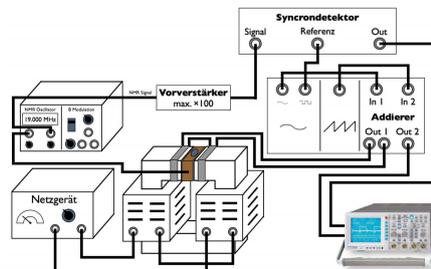


Figure 3: Setup for the measurement with the lock-in amplifier[1]

2. The lock-in amplifying setup seen in figure 3 is different to the first setup. Only the HF oscillator is connected the same way to the control unit but the antenna then is connected to an amplifier and a synchronous detector, which filters the signal. The signal is filtered so that the only signal remaining is the signal which has the same phase as the sine part of the wave on the solenoids. The modulating solenoids are

connected to an device adding a sine wave over a saw tooth wave. The resulting signal is also sent to the oscilloscope where the data is collected again.

In [figure 4](#), the resulting signal from the first setup in [figure 2](#) is shown. The amplitude of the absorption signal reaches a minimum when the frequency of the HF oscillator together with the modulated B -field hits the resonance frequency of the sample, which is given by [equation \(6\)](#). When the minimum of the signal and the zero crossing of the sine wave are at the same time, the resonance frequency to the before measured static magnetic field strength is found.

In [figure 5](#), the resulting signal from the second setup in [figure 3](#) with the lock-in method is shown. The minimum of the absorption is now the zero crossing of the differentiated curve from the HF antenna, shown in red. When the zero crossing of the signal and of the modulated magnetic field are at the same time, the resonance frequency to the before measured static magnetic field is found.

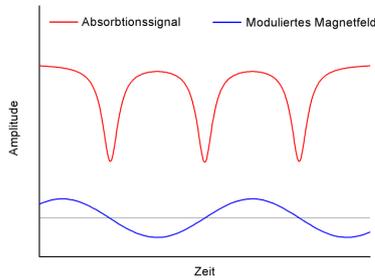


Figure 4: Signals of the modulated magnetic field with a sine wave frequency around the homogeneous B -field in blue and the absorption signal in red[1].

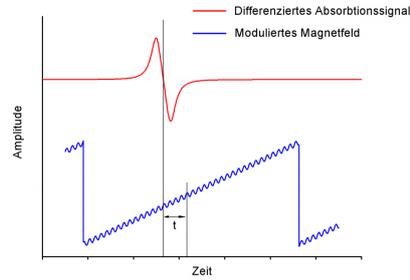


Figure 5: Signal from the lock-in method: Modulated B -field with saw tooth and overlain sine wave frequency. Derivative of the absorption signal in red[1].

4 Data Analysis and Result

All the uncertainties come from the errors of the used values through the Gaussian error propagation

$$\Delta A = \sqrt{\left(\frac{\partial A}{\partial x} \cdot \Delta x\right)^2 + \left(\frac{\partial A}{\partial y} \cdot \Delta y\right)^2}.$$

This is an example for a function A dependent on the variables x and y and their uncertainties.

4.1 Magnetic Field

It was noticed and expected that the Magnet coils heated up over time. Therefore, the magnetic field strength B decreased. In 50 min the field decreased around $\Delta B = 26$ mT. In the first half the field decreased around 66%. Because of that the field generating Coils were powered the whole time to have a mostly constant value of B . On top of that before and after each measurement the magnetic field strength was measured as well. The uncertainty on that comes from the error of reading a digital display with $a_B = 0.5$ mT on the last digit rectangular distributed.

$$\Delta B = \frac{0.5 \text{ mT}}{\sqrt{3}} \approx 0.3 \text{ mT}.$$

The error on the vertical position of the Hall sensor is estimated with $s_d = 0.5$ mm triangular distributed. The uncertainty follows with

$$\Delta d = \frac{0.5 \text{ mm}}{\sqrt{6}} \approx 0.2 \text{ mm}.$$

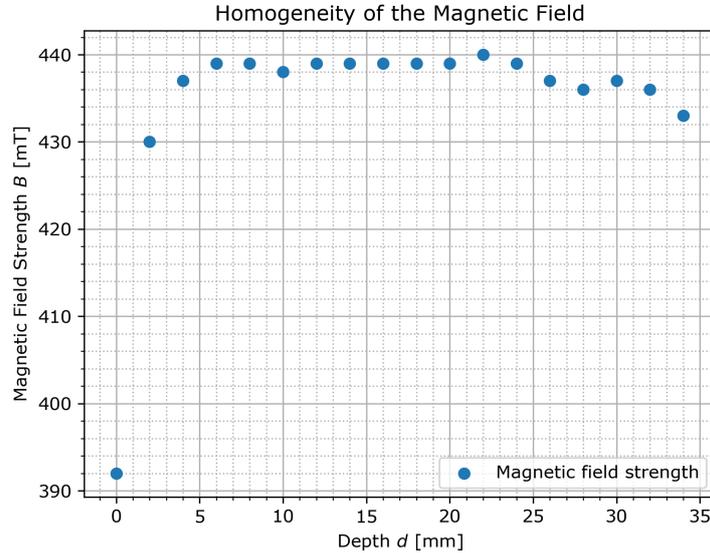


Figure 6: Magnetic field strength B dependent on the depth d of the Hall sensor in the measurement hole. The error on the values are smaller than the dots in the plot.

The measurement on the homogeneity of the magnetic field was conducted at the beginning of the experiment and was repeated later when the coils warmed up. Because of the reasons mentioned earlier the second measurement is used for the analysis and is seen in [figure 6](#). The depth is measured between the top part of the hole and the hall sensor. In the plot it is shown that at a depth of $d \geq 6$ mm the field was mostly homogeneous. The field strength dropped only a bit at a depth of $d \geq 26$ mm because the sensor was lowered into a metal coil which works as the sending antenna. This coil was expected to interfere with the magnetic field. Since the measurements only work when the samples are lowered into that metal coil/antenna, and the Magnetic Field strength was constant in that area, the magnetic field was deemed homogeneous enough. The further experiments were conducted with a magnetic field strength between $B = 452$ mT and $B = 437$ mT.

4.2 Nuclear Magnetic Moment

The nuclear magnetic moment μ_z is calculated by [equation \(3\)](#). Therefore the gyromagnetic ratio γ and the Nuclear spin quantum number I_z have to be determined by using [equation \(6\)](#) and [equation \(2\)](#). The resonance frequency is determined with a modulated sine wave from the resulting absorption spectrum with the setup one shown in [figure 2](#). This measurement is done with fluorine ^{19}F and Teflon.

4.2.1 With Fluorine

For the measurement analysed in [figure 7](#), a fluorine sample is used. For the measurement the first method with the modulated sine wave is used. This plot is considered a reference for all other measurements with that method. The structure looks always the same except for some difference in the values. Therefore later only the values are provided without a separate figure.

When the resonance frequency is not hit perfectly as described in [figure 4](#), the absorption minima are not arranged equidistant. Therefore, the time difference Δt_1 between the first and second minimum is not equal to the second time difference Δt_2 between the second and third minimum. With small changes in the HF oscillators frequency the different time differences between the minima get smaller. When the different values of Δt_1 and Δt_2 are plotted together with two fits the crossing of the fits marks the resonance frequency of the sample with the corresponding peak time difference Δt . The Values which were fitted had an uncertainty on the frequency and the peak time difference. The first was determined by the digital display of the frequency generator which resulted in

$$\Delta f = 30 \text{ Hz}$$

and for the later in

$$\Delta(\Delta t) = 40 \mu\text{s}.$$

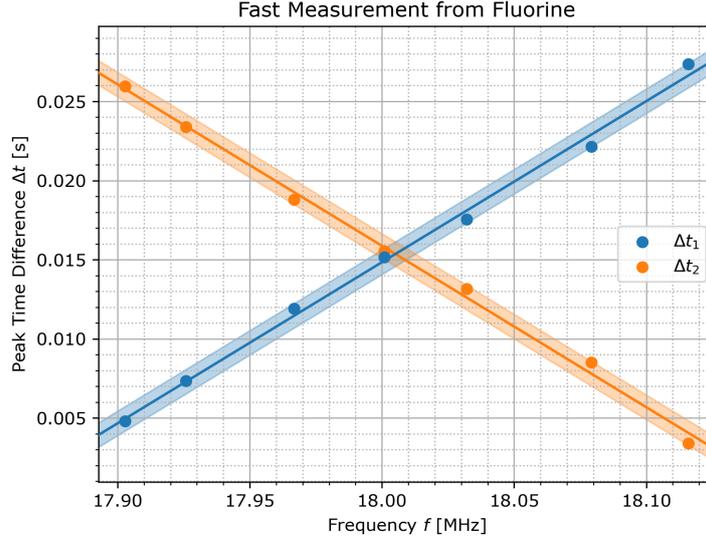


Figure 7: Time difference Δt_1 between two absorbance peaks (1&2) compared to the time difference Δt_2 between the second and next absorbance peaks (2&3). Δt is depending on the measured resonance frequency f .

For fluorine in [figure 7](#) this results in a resonance frequency of

$$f_{\text{fluorine}} = (18.005 \pm 0.005) \text{ MHz.}$$

The magnetic field strength had a value of $B = (448.5 \pm 0.3) \text{ mT}$. With that and [equation \(6\)](#), the gyromagnetic ratio is calculated to

$$\gamma_{\text{fluorine}} = (252.24 \pm 0.18) \times 10^6 \text{ rad/(s T).}$$

From there the nuclear magnetic moment is calculated with [equation \(3\)](#) to

$$\mu_{z\text{fluorine}} = (13.300 \pm 0.009) \times 10^{-27} \text{ J/T}$$

by using [equation \(2\)](#) to calculated I_z with $m_i = \frac{1}{2}$.

4.2.2 With Teflon

Teflon has the chemical formula $(\text{C}_2\text{F}_4)_n$. Carbon is an Atom with each 6 protons and neutrons. Therefore as mentioned in [section 2](#) the total nuclei spin quantum number is $I = 0$. Fluorine ^{19}F has a total spin quantum number $I = \frac{1}{2}$. Because of that, only the fluorine in the Teflon has an impact on the measurement and the result looks similar to [figure 7](#). The same experiment and analysis as in [section 4.2.1](#) were done here. This leads to the values shown in the following table.

Teflon	
magnetic field strength B	(448.0 ± 0.3) mT
frequency f [MHz]	(17.968 ± 0.006) MHz
gyromagnetic ratio γ	$(252.00 \pm 0.18) \times 10^6$ rad/(s T)
nuclear magnetic moment μ_z	$(13.287 \pm 0.010) \times 10^{-27}$ J/T

Table 1: Results of the measurement with Teflon

4.3 Gyromagnetic Ratio of the Hydrogen's Nucleus

The gyromagnetic ratio γ for a hydrogen's nucleus is measured with the modulated sine wave as for the fluorine and later with the lock-in method by using [equation \(6\)](#).

4.3.1 In Water

The hydrogen was provided as water (H_2O). In water two hydrogen atoms bond with one oxygen atom. Oxygen has equal to Carbon a total nuclei spin quantum number of $I = 0$. Therefore the only spin contributing to the measurement is the spin from the hydrogen nuclei. The results are shown in the table below.

Water	
magnetic field strength B	(448.0 ± 0.3) mT
frequency f [MHz]	(19.067 ± 0.006) MHz
gyromagnetic ratio γ	$(267.41 \pm 0.19) \times 10^6$ rad/(s T)
nuclear magnetic moment μ_z	$(14.100 \pm 0.010) \times 10^{-27}$ J/T

Table 2: Results of the measurement with Water

4.3.2 In Glycol

For glycol the same rules apply as for the hydrogen respectively water and for the teflon. Glycol ($\text{C}_2\text{H}_6\text{O}_2$) is made of carbon, oxygen and hydrogen atoms, therefore the only nuclei spin is contributed by the hydrogen.

Glycol	
magnetic field strength B	(447.5 ± 0.3) mT
frequency f [MHz]	(19.044 ± 0.006) MHz
gyromagnetic ratio γ	$(267.40 \pm 0.19) \times 10^6$ rad/(s T)
nuclear magnetic moment μ_z	$(14.110 \pm 0.010) \times 10^{-27}$ J/T

Table 3: Results of the measurement with Glycol

4.4 Proton Resonance Frequency of Hydrogen with Lock-in Method

For the lock-in method different frequencies were taken and the zero point time difference Δt was measured. Those values seen in figure 8 were then fitted and the frequency were $\Delta t = 0$ was interpolated. The error on Δt changed as well to

$$\Delta(\Delta t) = 0.04 \text{ s.}$$

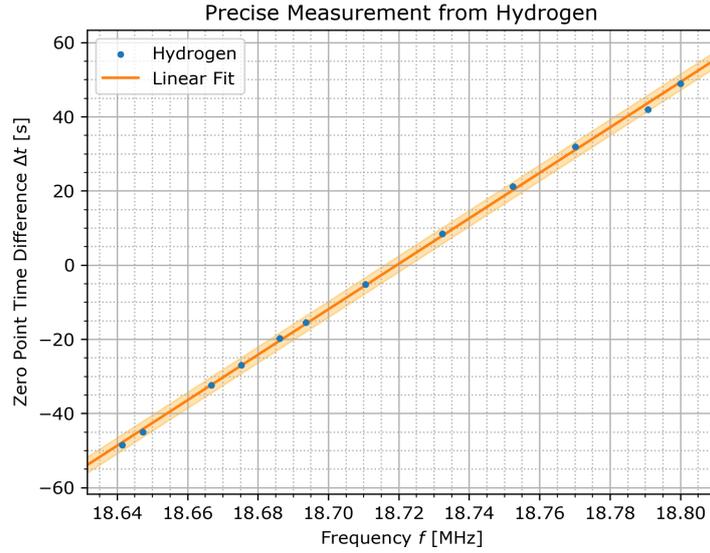


Figure 8: Resonance frequency f for the hydrogen sample with the time difference depending on the HF-frequency from the oscillator.

This yields the results seen in the table below.

Water (Lock-in-Method)	
magnetic field strength B	$(438.0 \pm 0.4) \text{ mT}$
frequency f [MHz]	$(18.720 \pm 0.003) \text{ MHz}$
gyromagnetic ratio γ	$(268.5 \pm 0.3) \times 10^6 \text{ rad}/(\text{s T})$

Table 4: Results of the precise measurement with Water

5 Discussion

5.1 Final Results

The final results of the measurements of the nuclear magnetic moment of ^{19}F fluorine are shown in [table 5](#).

Nuclear Magnetic Moment μ_z of fluorine	
Fluorine	$(13.300 \pm 0.009) \times 10^{-27} \text{ J/T}$
Teflon	$(13.287 \pm 0.010) \times 10^{-27} \text{ J/T}$

Table 5: Results for nuclear magnetic moment of fluorine

For the hydrogen ^1H the results of the measurements with glycol and water are shown in [table 6](#) for both measurement types.

Gyromagnetic Ratio γ of Hydrogen	
Glycol	$(267.40 \pm 0.19) \times 10^6 \text{ rad/(s T)}$
Water	$(267.41 \pm 0.19) \times 10^6 \text{ rad/(s T)}$
Water (Lock-in method)	$(268.5 \pm 0.3) \times 10^6 \text{ rad/(s T)}$

Table 6: Results for the gyromagnetic ratio of hydrogen

5.2 Error

The main error contributing to the gyromagnetic ratio γ was the systematical error on the magnetic field strength. This varied between the first measurements and the Lock-in method drastically. The contribution in the first measurements was 2:1 magnetic field to frequency error. In contrast to that the Lock-in-Method produced an error ratio of 50:1. This has several reasons, first of all the frequency measurement had a very low systematic error and we did several measurements on the frequency to minimize the statistical error. So the error on the frequency in general was low, and the Lock-in-Method further reduced the error on the frequency. The magnetic field strength in contrast was not perfectly stable through the whole experiment and had a huge systematical error and was measured once per sample. This had the greatest impact on the error of our results.

5.3 Comparison with Expected Results

Whether a measured value is tolerable with the literature value or not can be determined with a t-test

$$t = \frac{|\hat{x} - \hat{y}|}{\sqrt{(\Delta x)^2 + (\Delta y)^2}}. \quad (7)$$

With a significance level of $\alpha = 0.05$ a divergence of $t \geq 2$ is considered significant. Is the t-value smaller, the result is compatible with the literature value.

5.3.1 Magnetic Field

The magnetic field was expected to be homogeneous in the majority of the relevant space and it was. One slightly surprising peculiarity was that the magnetic field was getting lower over time, but this was not that influential because the process was very slow after some time.

5.3.2 Nuclear Magnetic Moment of Fluorine

the nuclear magnetic moment μ_z is provided in literature as a multiple of the nuclear magneton μ_N . It has the literature value[3]

$$\mu_N = (5.050\,783\,739\,3 \pm 0.000\,000\,001\,6) \times 10^{-27} \text{ J/T}. \quad (8)$$

From [equation \(3\)](#) in combination with [equation \(4\)](#) and [equation \(5\)](#) the equation $\mu_z = g_I m_i \mu_N$ can be deduced. So the literature value of the nuclear magnetic moment of fluorine[2] is

$$\mu_z = (2.628\,321 \pm 0.000\,004) \mu_N = (13.275\,08 \pm 0.000\,02) \times 10^{-27} \text{ J/T}. \quad (9)$$

With a t-test as shown in [equation \(7\)](#) the measured nuclear magnetic moment μ_z is compared with the literature value.

t-test for μ_z	
Fluorine	$t = 2.76$
Teflon	$t = 1.19$

Table 7: t-test for the nuclear magnetic moment of fluorine

The value measured with the fluorine sample is > 2 and therefore significantly apart from the literature. With the measurement of the Teflon sample a result is achieved that is tolerable with the literature value. For the fluorine the value could be apart from the expected one because the magnetic field was not constant over time. Furthermore, no instruments had an uncertainty mentioned in the manuals. If we underestimated the error that can lead to a big t-value.

5.3.3 Gyromagnetic Ratio of the Hydrogen's Nucleus

The literature value for the gyromagnetic ratio of hydrogen measured with water[4] is

$$\gamma_H = (267.515\,319\,4 \pm 0.000\,001\,1) \times 10^6 \text{ rad/(s T)}. \quad (10)$$

t-test for γ	
Glycol	$t = 0.61$
Water	$t = 0.55$
Water (Lock-in method)	$t = 3.28$

Table 8: t-test for the gyromagnetic ratio of hydrogen

As clearly visible in [table 8](#) the values of the gyromagnetic ratio of the hydrogen nuclei fit really good for the fast measurement from water and glycol. The Lock-in-Method yielded a significant difference between the literature value and our measurements. This could be an outlier but probably the magnetic field was not stable, or the zero points were not analyzed properly. In any case the values are reasonable close for this low budget setup.

5.4 Improved Methods

The setup from the experiment was pretty good, it was possible to get really close to the literature values. But there are some improvements possible. First of all a the coils for the main magnetic field could be powered by a constant current power supply, this achieves a more constant magnetic field strength which is not susceptible to heat induced current drops and therefore magnetic field strength drops. This would provide more accurate readings and would eliminate the need for waiting after turning on the coils.

Another easy and good improvement would be a new and better hall sensor without a loose connection and with a resolution better than one mT and for this matter in general a known error. This is especially important, because the error on γ was mainly because of the error on the magnetic field strength. The contribution from the magnetic field strength error was in the normal measurement two times higher and in the Lock-in-Method fifty times higher, in contrast to the contribution from the error on the frequency.

The last improvement would be to measure every probe with the Lock-in-Method, after the Hall sensor was upgraded. Therefore another Oscilloscope with a better time resolution for such long intervals would be useful.

With those three improvements the error of the setup could be drastically improved.

6 Conclusion

The measurements done in this experiment show that it is possible to measure the gyromagnetic ratio γ fairly precise with a low budget setup. It also illustrates the usefulness of this non destructive method for analyzing materials. The Lock-in-Method is in theory more precise than the other method, but the measurements were limited by the error on the magnetic field strength anyways. This measurement took longer than the others, so the effect of the non stable magnetic field was more important.

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C Literature

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D Attachment

D.1 Lab Book

Lab book: 6. NMR

1. magnetic field

vertical distance d in mm	B in mT	d in mm	B in mT
3	457	0	392
5	463	2	430
7	460	4	437
9	461	6	439
11	459	8	439
13	460	10	438
15	460	12	439
17	460	14	439
19	460 458	16	439
21	458	18	439
23	457	20	439
25	456	22	440
27	454	24	439
29	450	26	437
31	452	28	436
33	450	30	437
35	449	32	436
37	452	34	433

magnetic field: $U = 9,5V, I = 3,32A$

- Fluorine: 1. $f = 17,9848 \text{ MHz}$
 $d = 30 \text{ mm}$ \hookrightarrow new Felle 3 (nF3)
 $a = 0,5 \text{ mm}$ Δ distributed 2. $f = 17,9749 \text{ MHz}$
 \hookrightarrow nF4
 3. $f = 17,9762 \text{ MHz} \rightarrow$ nF5
 4. $f = 17,9667 \text{ MHz} \rightarrow$ nF6

B field check: $B = 448 \text{ mT}$

- Teflon: $-C_2F_4-$
 1. $f = 17,9394 \text{ MHz} \rightarrow$ nF7
 2. $f = 17,9328 \text{ MHz} \rightarrow$ nF8
 3. $f = 17,9206 \text{ MHz} \rightarrow$ nF9
 4. $f = 17,9123 \text{ MHz} \rightarrow$ nF10

$B = 446 \text{ mT}$

- H_2O : 1. $f = 19,0122 \text{ MHz} \rightarrow$ nF11
 2. $f = 19,0098 \text{ MHz} \rightarrow$ nF12
 3. $f = 19,0108 \text{ MHz} \rightarrow$ nF13

- $d = 30 \text{ mm}, a = 0,5 \text{ mm}$
 1. $f = 17,6702 \text{ MHz} \rightarrow$ nF20
 2. $f = 17,6642 \text{ MHz} \rightarrow$ nF21
 3. $f = 17,6578 \text{ MHz} \rightarrow$ nF22
 4. $f = 17,6542 \text{ MHz} \rightarrow$ nF23
 $B = 439 \text{ mT}$

$d = 30 \text{ mm}, a = 0,5$

H_2O : 4. $f = 19,0142 \text{ MHz} \rightarrow nF74$

5. $f = 18,9984 \text{ MHz} \rightarrow nF75$

$B = 446 \text{ mT}$

Glykol
 $C_2H_6O_2$ 1. $f = 18,9900 \text{ MHz} \rightarrow nF76$

2. $f = 18,9834 \text{ MHz} \rightarrow nF77$

3. $f = 18,9766 \text{ MHz} \rightarrow nF78$

4. $f = 18,9614 \text{ MHz} \rightarrow nF79$

$B = 445 \text{ mT}$

Break
 $B = 439 \text{ mT}$

Lock-in-measurement

H_2 : 7. $f = 18,6862 \text{ MHz} \rightarrow nF24/25$

2. $f = 18,6753 \text{ MHz} \rightarrow nF26$

3. $f = 18,6472 \text{ MHz} \rightarrow nF27$

4. $f = 18,6336 \text{ MHz} \rightarrow nF28$

5. $f = 18,7105 \text{ MHz} \rightarrow nF29$

6. $f = 18,7324 \text{ MHz} \rightarrow nF30$

7. $f = 18,7524 \text{ MHz} \rightarrow nF31$

8. $f = 18,7702 \text{ MHz} \rightarrow nF32$

9. $f = 18,7908 \text{ MHz} \rightarrow nF33$

10. $f = 18,6668 \text{ MHz} \rightarrow nF34$

11. $f = 18,8000 \text{ MHz} \rightarrow nF35$

12. $f = 18,6415 \text{ MHz} \rightarrow nF36$

$B = 437 \text{ mT}$

Phosphor $f = 18,6957 \text{ MHz}$

09.23 $B=449\text{mT}$ $u_g=0,5\text{ml}$ \square -distributed
 $a_f=0,00005\text{MHz}$ \square

Fluorine \rightarrow

Sample	measurement	frequency f in MHz	File (hP)
Fluorine	1	18,1759	37
	2	18,0792	38
	3	18,0320	39
	4	18,0009	40
	5	17,9667	41
	6	17,9258	42
	7	17,9028	43
$B=448\text{mT}$ Teflon	1	18,0661	44
	2	18,0389	45
	3	18,0036	46
	4	17,9636	47
	5	17,9314	48
	6	17,8980	49
	7	17,8687	50
$B=448\text{mT}$ H_2O	1	19,7290	51
	2	19,7528	52
	3	19,7297	53
	4	19,0843	54
	5	19,0403	55
	6	19,0112	56
	7	18,9728	57
$B=448\text{mT}$ Glykol	1	19,7576	58
	2	19,7307	59
	3	19,0983	60
	4	19,0628	61
	5	19,0328	62
	6	18,0088	63
	7	18,9781	64
	8	18,9443	65
$B=447\text{mT}$	H_2O	Best values	66
	Glykol	as seen	67
	Teflon	on millirope	
$B=447\text{mT}$	Fluorine	17,8837	

Signed by aghisbawt 23/9/24 : 

Figure 9: Lab book